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GB 2257437 A GB 1391357 A GB 1387941 A
GB 1228646 A GB 1160566 A WO 94/12991 A

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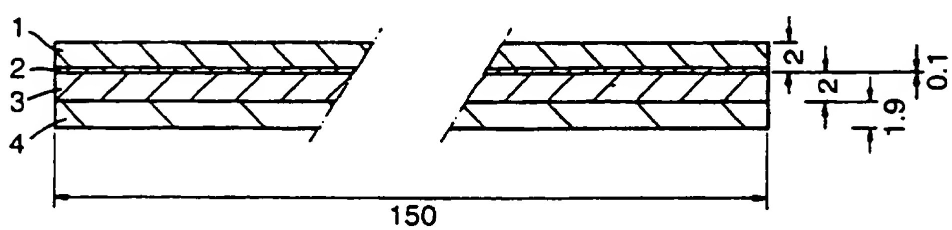
(54) **Superconductor and energy storage device**

(57) A self-supporting superconductor comprises a tape having a carrier layer 1 supporting a cryostable superconducting material 2. In an embodiment (Figure 6), a carrier (10) of steel or stainless steel tape is electroplated and bonded by solder and induction heating to a web (14) of NbTi 2, a web (19) of normal metal e.g. Cu or Al 3 is bonded to the laminated superconductor by solder and induction heating. An insulating layer 4 is provided through which heat can be extracted in the event of the material quenching. The tape is formed into coils (Figures 2 to 5) to make a superconducting magnetic energy store or SMES. Up to seven coils may be used together to form a taurus (Figure 3). The size and disposition of the coils, their stability and energy storage capacity are discussed.

Fig.1.



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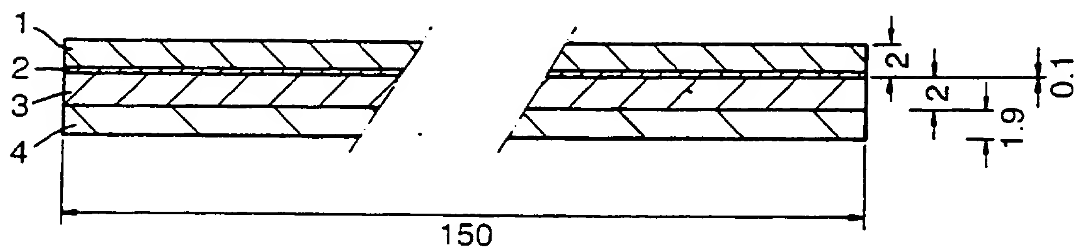
At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

Fig.1.



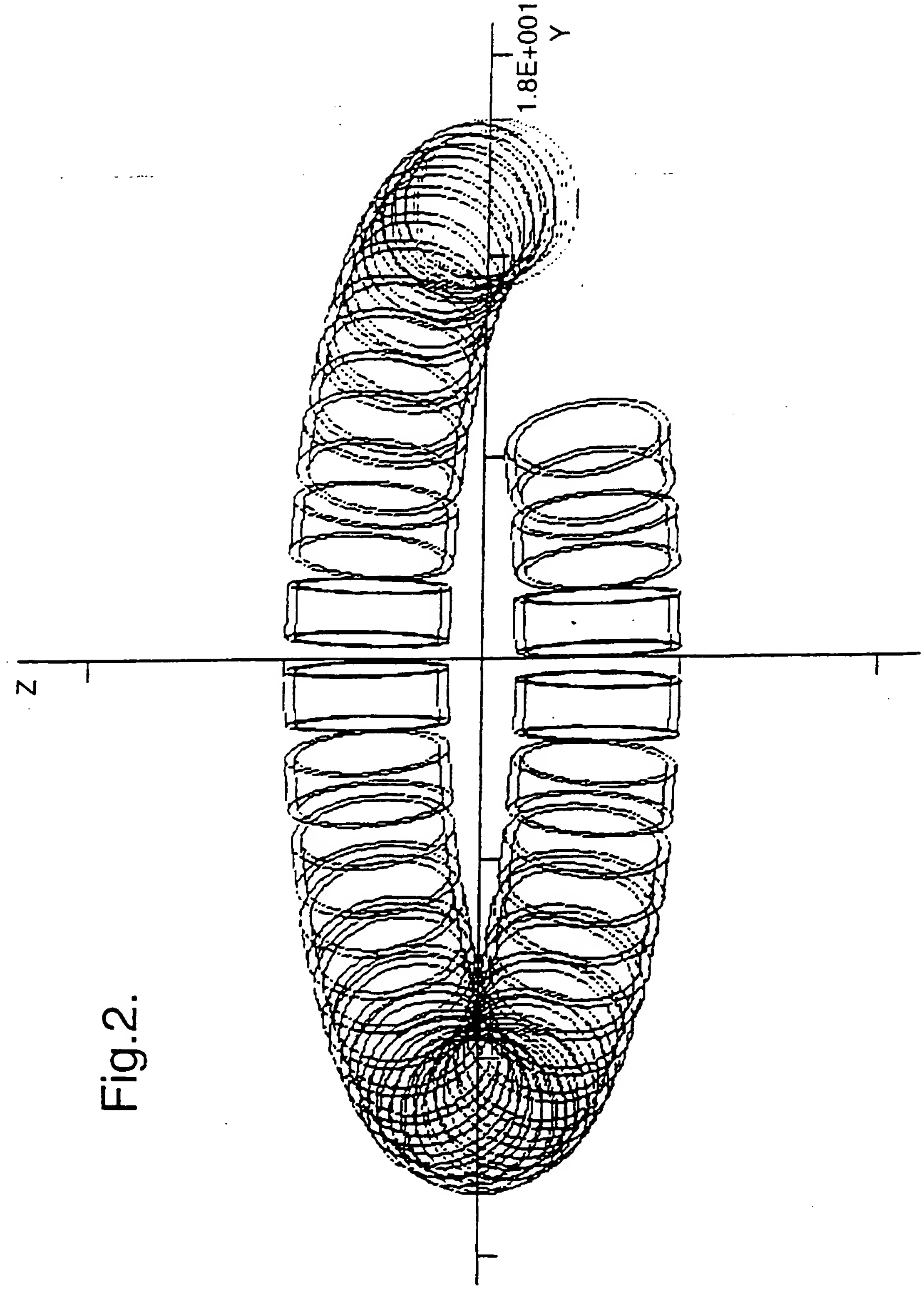


Fig.2.

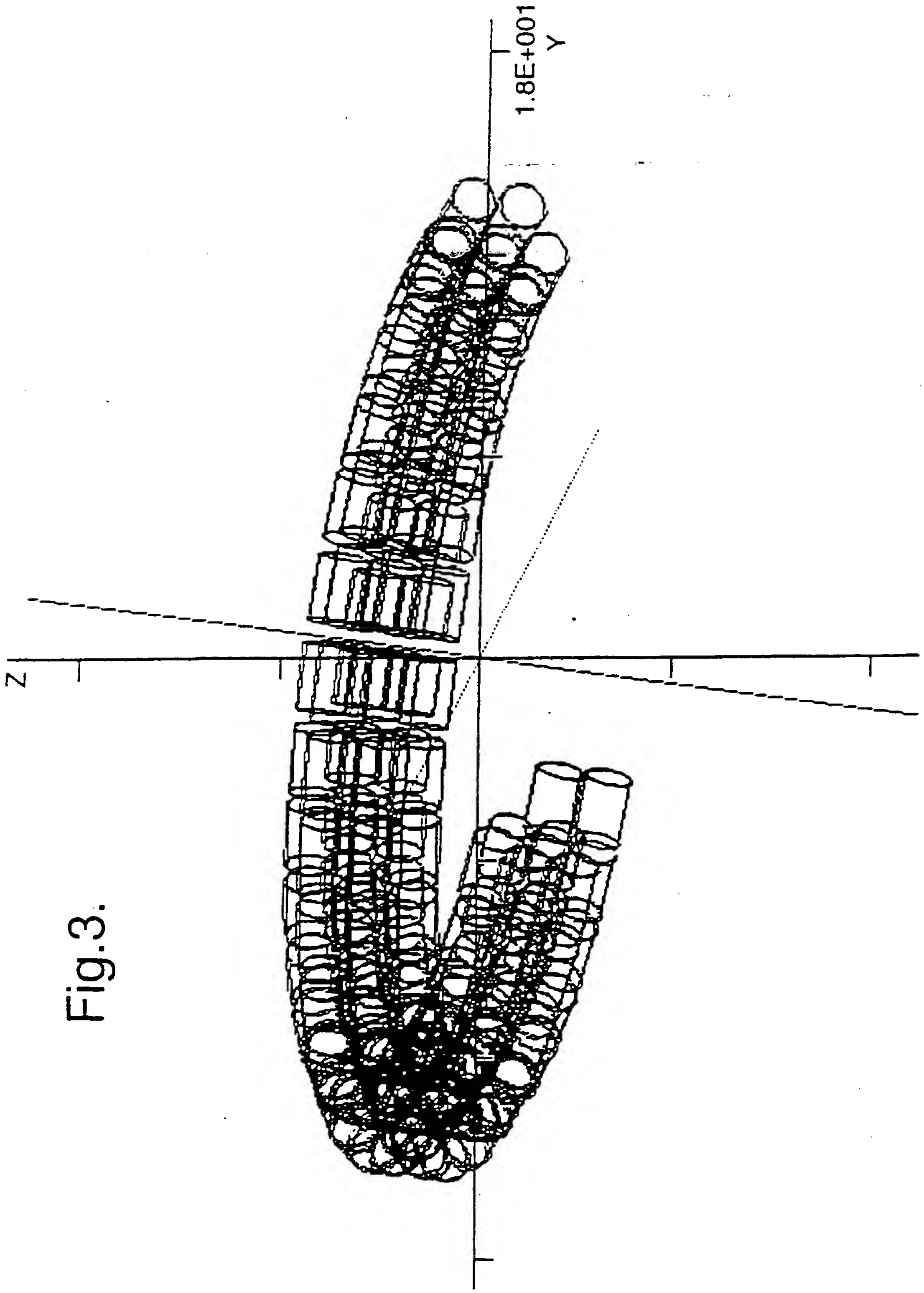


Fig.3.

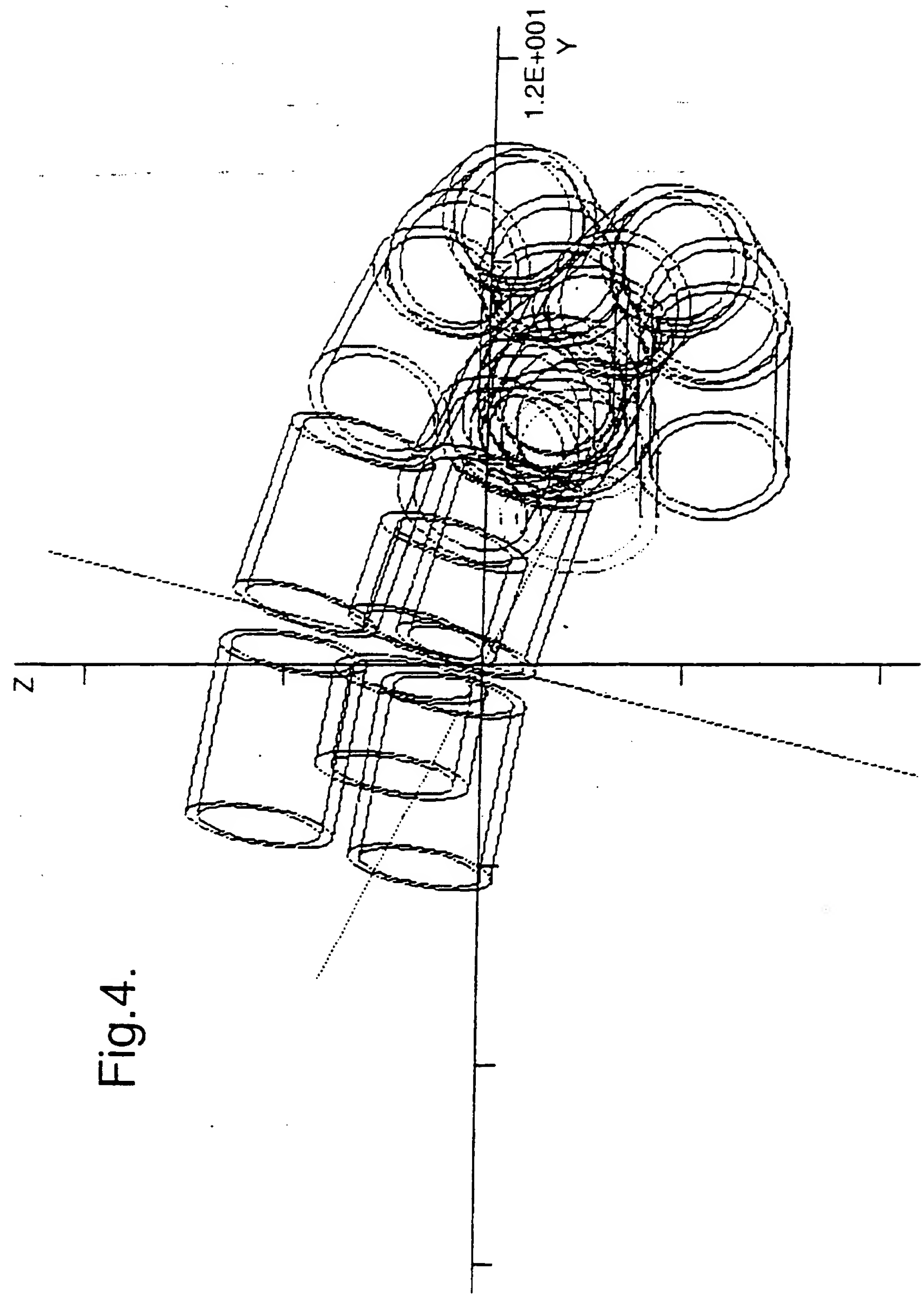


Fig.4.

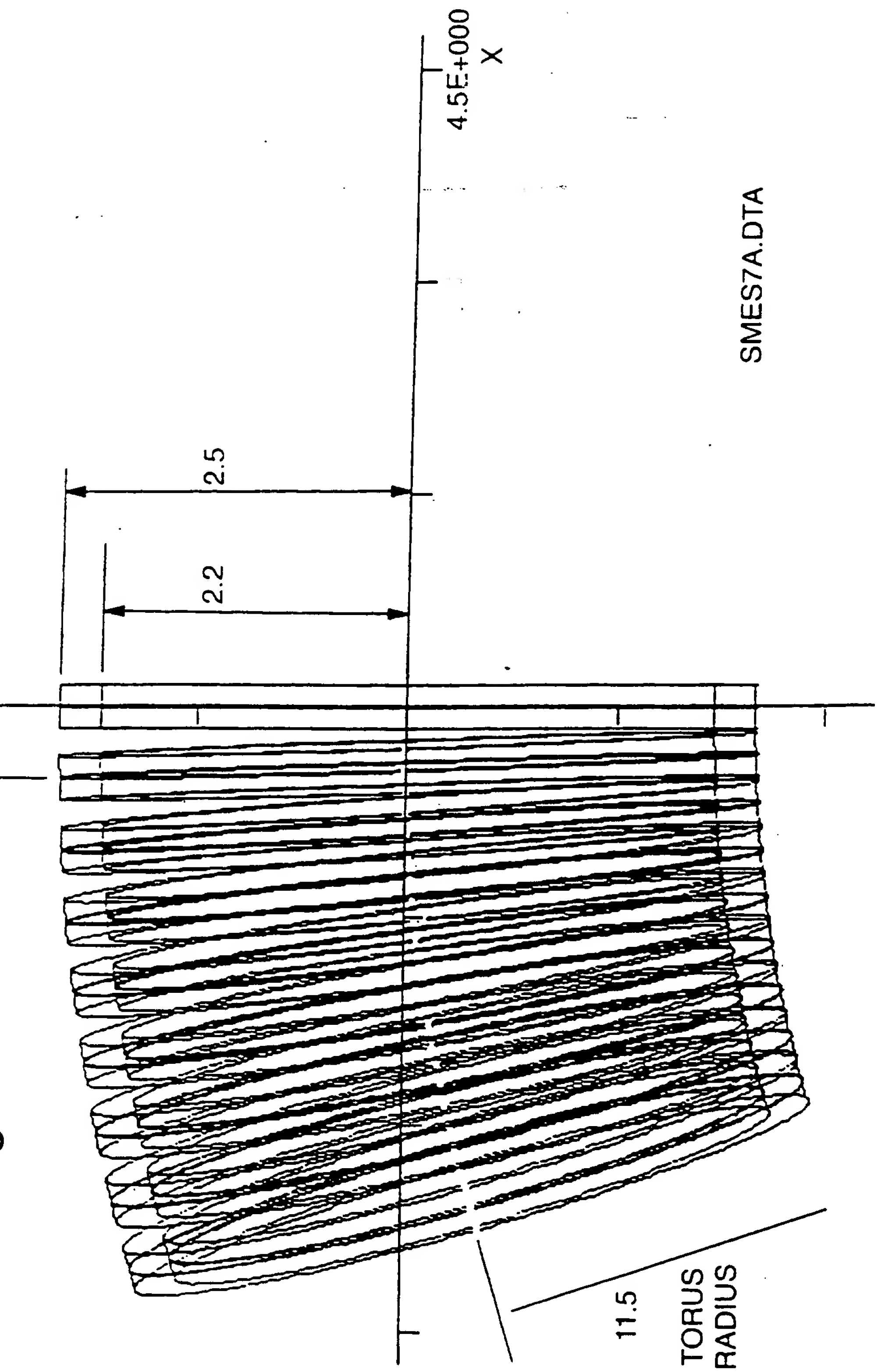
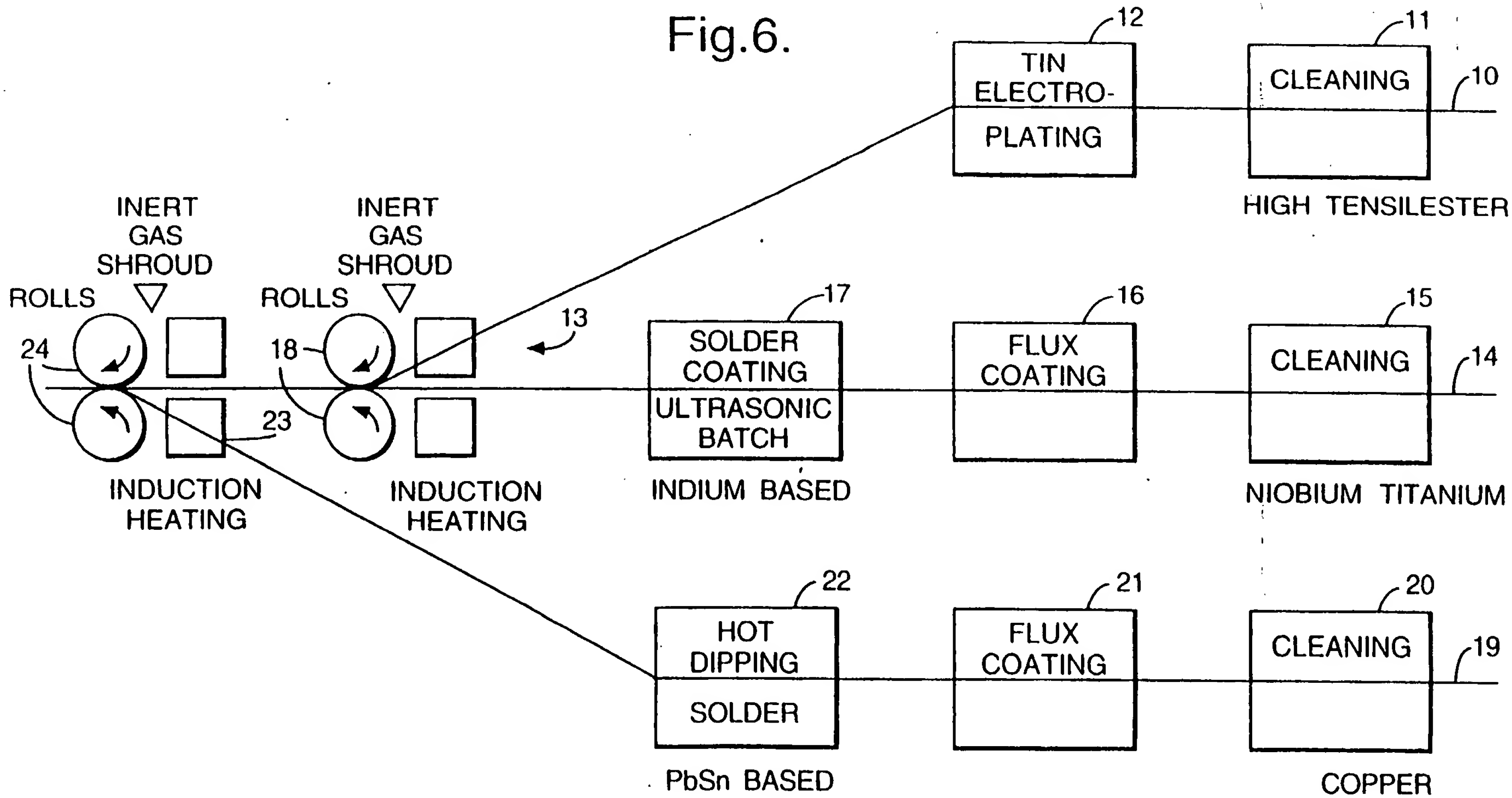


Fig.5.

Fig.6.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SUPERCONDUCTOR AND ENERGY STORAGE DEVICE

The invention relates to a superconductor and also to an energy storage device incorporating such a superconductor.

Recently, energy storage devices have been developed which make use of magnetic fields to store energy. These are fabricated using superconducting electrical coils arranged in such a way that they can be rapidly discharged and charged. Conventionally, this technique is known as Superconducting Magnetic Energy Storage (SMES).

SMES systems are able to store very high quantities of energy, typically up to 100 MJ and conceivably 10,000 MJ. One of the problems, however, with SMES systems is their high cost. One way of reducing this is described in our copending European Patent Application No. 0653098 which describes the use of an array of coils. This approach can reduce material requirements by up to 20%.

SMES systems also have to deal with the effects of stress which can cause small "packets" of heat to develop which raise the temperature of coil windings locally such that at the raised temperature the conductor cannot support the electric super current of the magnet winding. The composite then goes normal and the magnet fails.

Various strategies are in use to stop local deformation. The windings are accurately laid to minimise voids into which turns may migrate under load, windings are impregnated (either with epoxy glues to bind turns, or fillers to obviate voids), and windings are mounted on formers with profiled clamps to balance electromagnetic forces. Attempts have also been made to reinforce conductor to increase the effective elastic modulus, and yield strength of the composite. For a given force field and winding geometry, elastic deformation is proportional to I/E, and if the yield stress is exceeded, permanent deformation of the winding results such that it is unlikely to be re-energisable.

In accordance with the present invention, we provide a self-supporting superconductor comprising a tape having a carrier layer supporting a cryostable superconducting material.

We have developed a new type of superconductor which is self-supporting and cryostable which is particularly suitable for use in energy storage devices. This should be contrasted with conventional superconductors which comprise composites of the fine filament type. Not only does the cryostable nature of the tape allow rapid recovery of the superconducting state in the case of the generation of heat locally but it also makes the superconductor much easier to manufacture as will be described below.

The tape can be used in a variety of forms but conveniently is fabricated in the form of a coil and it will be appreciated that large size coils can be fabricated typically having radii in the range 3-10m, preferably about 5m.

By "tape" we wish to contrast the inventive superconductor from conventional filamentary superconductors. Typically, the tape will have dimensions in the order of mm. For example, it may have a thickness in the order of 4.5mm.

The term "cryostable" indicates that heat can be extracted from the tape more quickly than it can be generated so as to allow the superconducting condition to be recovered automatically.

Conveniently, the cryostable superconducting material is in the form of a laminate having a superconducting layer and a layer of material which conducts normally. The superconducting layer is preferably NiTi while the normally conducting layer may be any conventional material such as copper or aluminium.

The carrier layer is preferably ferro-magnetic and in the past such materials have not been used in composite superconducting materials as the magnetic field of the component such as a winding in which they are incorporated

is perturbed. However, in the present case, a ferro-magnetic material can be used because the high permeability of the material, distributed across the (typically flat) face of the superconductor will help to stabilise the superconductor against flux jumps. Furthermore, in the case of an energy store, field perturbation is not a problem since the energy depends on the average value of magnetic field.

In some cases, however, the carrier layer could be a non-ferro-magnetic material such as stainless steel.

The new superconductor is particularly useful in the fabrication of an energy storage device in which typically it will be in the form of a coil. Most conveniently, a set of coils are provided arranged in the form of a torus.

In some cases, the cross-section of the torus may be defined by a single coil but preferably the cross-section is defined by an array of coils such as a hexagonal array for the reasons outlined in our earlier European Patent Application No. 0653098.

Cooling of the superconducting material can be carried out in any conventional manner using helium or cryo-coolers and the like.

In accordance with a second aspect of the present invention, a method of manufacturing a self-supporting superconductor according to the first aspect of the invention comprises bonding separate tapes defining the carrier layer and superconducting material respectively.

Conveniently, the superconducting material itself is formed as a laminate comprising a tape of superconductor and a tape of normal conductor bonded together.

The bonding process is typically roll bonding and may comprise one or both of ultrasonic soldering and continuous induction heating.

Some of the advantages of the new tape, particularly when incorporated in an energy storage device are:

- Fewer large machined components.

- No resin impregnation process (also allows possibility of reworking coils).
- Separates the functions of insulation and support.
- Enhanced cooling for cyrostability.

The main disadvantages of resin as a structure element are:

- Requires filler to match thermal contraction (difficult impregnation)
- Low elastic modulus (7 10^9 cf. 2.1 10^{11} Cu
- Brittle at cryogenic temperatures - effect of stress contractions and mechanical cycling difficult to predict.

Some examples of tapes according to the invention and energy storage devices incorporating such tapes as well as a method of manufacturing the tape will now be described with reference to the accompanying drawings, in which:-

Figure 1 is a cross-section through a tape;

Figures 2-4 partially illustrate three examples of toroidal arrays of coils;

Figure 5 is an example of a further toroidal array, only part of which is shown; and,

Figure 6 is a schematic block diagram of a manufacturing plant.

The tape shown in Figure 1 in cross-section has a steel carrier or supporting layer 1 having a thickness of 2mm and on which is supported a 0.1mm thick layer of Niobium Titanium 2. This constitutes the superconducting material. A 2mm thick layer of copper 3 is provided on the layer 2 (to provide a conduction path if part of the superconducting material turns normal) and an insulating layer 4 in the form of a conventional polymer material is secured to the copper layer 3. In use, the layer 4 will be exposed to a coolant to enable heat to be extracted from the tape. The assembly is cryostable in the sense that

heat can be extracted from the tape sufficiently quickly to allow the superconducting material to revert to a superconducting condition in the event of a quench.

The width of the tape as shown is 150mm.

When the tape is to be utilised in an energy storage device, it will be formed into a number of coils and these can be organised into a toroidal magnet in a number of ways as shown in Figures 2-5.

Figure 2 shows 34 5m diameter coils in a 13.6m radius torus. The conductor is a 7.5mm thick Cu/Nb-Ti composite, co-wound with a 1.8mm thick steel strip on the outside, for the first 11 layers (out of 22) only. The mass of steel is 126 tonnes, whose inclusion reduces the specific energy from 6.26 to 5.69 MJ/tonne.

Figure 3 replaces each 34 5m diameter coil with 7 1.5m diameter coils in a hexagonal array. The smaller coil radius allows a higher current density. However, this current density does not appear to allow cryostatic stability.

Figure 4 shows an array generating a higher peak field (6T as against 4.5T). The arrangement is 12 groups of 3 3m diameter coils in a ca. 10m radius torus.

The constructions shown in Figures 2-4 have been modelled on computer and the results of this are set out in Table 1 below. This describes the modelling of 5 systems. SMES5G is the system shown in Figure 2 while SMES5H has a similar geometric configuration to Figure 2 but without reinforcement. The current density in this case is chosen to be low enough to result in acceptable hoop stress.

SMES6D corresponds to the Figure 3 example and SMES6E to the Figure 4 example. SMES6F corresponds to Figure 4 but with a 4.5T peak field. In this case, the individual coils can be larger at 3.8m radius and the torus smaller.

In all cases, a maximum stress in a conductor of 2×10^8 Pa and an operating current of 15 kA is chosen. Furthermore, in all cases the aspect ratio of the conductor is 10/1 (chosen as the largest compatible with ease of

handling). The cooled surface is 70% of one of the flat sides.

TABLE 1

COMPARISON OF SYSTEM CONCEPTS - STRESS LIMITED TO 2 10^8 NM^{-2}

MODEL	Units	Bmax Tesla	a1 metres	a2 metres	2b metres	R metres	Joverall A/m^2	Emax MJ	M tonnes	E/M MJ/ton
SMES5G	34	4.5	2.238	2.37	1.6	13.6	1.67E+07		580	
	34	1.8	2.373	2.495	1.6		1.97E+07		669	
(steel reinforced)								7830	1249	6.26
SMES5H	34	4.5	2.192	2.5	1.6	13.6	1.51E+07	7340	1681	4.37
SMES6D	68	4.5	0.675	0.75	1.6	12.21	5.00E+07			
	102		0.675	0.75	2	13.6	5.00E+07			
	68		0.675	0.75	2.4	14.99	5.00E+07			
(not cryostable)								5370	1073	5.00
SMES6E	12	6	1.25	1.574	2	7.332	2.19E+07			
	24	6	1.25	1.5	3.6	11.33	2.19E+07			
								9360	1877	4.98
SMES6F	12	4.5	1.667	1.9	2.67	5.5	2.19E+07			
	24	4.5	1.667	1.85	4.8	8.5	2.19E+07			
								11050	2324	4.75

Figure 5 illustrates a particularly preferred arrangement in which the tapes are wound into coils having a double pancake form. In this example, each pancake has 50 turns of ribbon with an inner radius of 2.2m, an outer radius of 2.5m and a module width of 0.31m. There will be 170 modules (340 coils) arranged on a 11.5m radius torus and this will result in stored energy of 8.66×10^9 J when carrying a current of 15,000A. The maximum stress (in steel) is 5×10^7 NM^{-2}. In this case, the mass of the conductor or tape will be made up as follows:

- steel	597.3
- NbTi	23.8
- copper	684.1
TOTAL	1305.2 tons

6.64 MJ/ton

The same 170 modules in a 13.5m radius torus have stored energy of $7.67\ 10^9$ J.

A compact system has:

* more stored energy
* less stray field
* less refrigeration power.

MAGNETIC STABILITY

Stability against flux jumping can be provided in three ways:

* adiabatic stability. Requires superconductor of small dimensions (ca. 100μm).
* dynamic stability - to remove the heat dissipated in a flux jump more quickly than the flux jump can propagate. Requires normal conductor to remove heat and damp flux movement.

* cryostatic stability - provide a low-resistance path to carry the current while the superconductor recovers.

ADIABATIC STABILITY

Condition for stability is:

$$\beta = \frac{\mu_0 J_c^2 a^2}{\gamma C(\theta_c - \theta_0)} < 3$$

J_c *critical current*
a *dimension perpendicular to field*
γ *density*
C *specific heat*
θ_c *critical temperature*
θ_0 *ambient temperature*

B Tesla	Jc A/m^2	θc	B min for flux jump	ß(axial)	ß(radial)
0.00E+00	8.00E+09	9.50E+00	3.32E-01	6.87E+00	1.55E+07
1.00E+00	4.30E+09	9.00E+00	3.16E-01	2.19E+00	4.93E+06
2.00E+00	3.30E+09	8.00E+00	2.81E-01	1.63E+00	3.67E+06
3.00E+00	3.10E+09	7.70E+00	2.70E-01	1.56E+00	3.52E+06
4.00E+00	2.50E+09	7.30E+00	2.54E-01	1.15E+00	2.58E+06
4.50E+00	2.20E+09	7.50E+00	2.62E-01	8.35E-01	1.88E+06

Hence

* Conductor is adiabatically stable for axial fields

* not adiabatically stable for radial fields,
  - but B_r values not much greater than minimum value for flux jump,

except next to gaps.

DYNAMIC STABILITY

Balance the heat dissipated by flux movement through the composite against heat going into warming, and heat lost to the exterior, over the time characteristic of magnetic diffusion

$$\beta = \frac{\mu_0 \lambda^2 J_c^{\,2} b^2}{4 \gamma C (\theta_c - \theta_0)} < 3 \left[1 + \frac{h \mu_0 \lambda b^2}{\pi^2 a \gamma C}\right] / (1 + 3\, i)$$

λ *proportion of superconductor*
a, b *dimensions of composite*
h *heat transfer coefficient*
i I/I_c

B	J_c	θ_c	β	I (A) 0.00E+00 criterion	5.00E+03 criterion	1.00E+04 criterion	1.50E+04 criterion
0.00E+00	8.00E+09	9.50E+00	3.87E+04	1.30E+04	1.29E+04	1.27E+04	1.24E+04
1.00E+00	4.30E+09	9.00E+00	1.23E+04	1.30E+04	1.28E+04	1.21E+04	1.12E+04
2.00E+00	3.30E+09	8.00E+00	9.18E+03	1.30E+04	1.26E+04	1.16E+04	1.02E+04
3.00E+00	3.10E+09	7.70E+00	8.79E+03	1.30E+04	1.25E+04	1.14E+04	9.89E+03
4.00E+00	2.50E+09	7.30E+00	6.46E+03	1.30E+04	1.23E+04	1.07E+04	8.77E+03
4.50E+00	2.20E+09	7.50E+00	4.70E+03	1.30E+04	1.21E+04	1.02E+04	8.01E+03

* Conductor is dynamically stable above 1 T

HYSTERESIS LOSSES

$$Q = \frac{\delta B^2}{2\mu_0}\Gamma$$

$$\text{where } \Gamma = \frac{\alpha}{3} \qquad \alpha < 1$$
$$= (1/\alpha - 2/3\alpha^2) \qquad \alpha > 1$$
$$\alpha = \frac{\delta B}{\mu_0 J_c a} = \frac{\delta B}{B_p}$$

B_p is the field which just penetrates the superconductor.

	"LARGE PULSE" 50MW for 50s		"SMALL PULSE" 10MW for 5s	
start current	15000	12500	15000	10000
end current	12500	9400	14950	9930
δB Tesla	-0.75	-0.93	-0.015	-0.021
α	2.72	2.74	0.018	0.018
Q (J/m^3/cycle)	$6.22\ 10^4$	$9.5\ 10^4$	$1.6\ 10^2$	$3.2\ 10^2$
estimated over whole magnet	$1.25\ 10^5$	$1.9\ 10^5$	$3.2\ 10^2$	$6.4\ 10^2$

NB Cryostatic stability requires transfer of dissipation equivalent to $7.5\ 10^5\ J/m^3$/sec.

A method of manufacturing the tape and apparatus for carrying this out is shown in Figure 6.

A web of high tensile steel 10 is drawn off a storage roll (not shown) and fed through a cleaning unit 11 to a tin electro-plating unit 12. Following electro-plating, the web is fed to an induction heating unit 13. A web of Niobium Titanium 14 from a storage roll (not shown) is fed through a cleaning unit 15 to a flux coating unit 16 and from there to a solder coating/ultrasonic bath unit 17. The resultant coated web is also fed to the induction heating unit 13 and the two webs 10,14 are then fed between rollers 18. This causes the two webs to be bonded together, the bonding process being carried out in an inert gas atmosphere.

A further web 19 of copper from a storage roll (not shown) is fed through a cleaning unit 20 to a flux coating unit 21 and thereafter to a hot dipping solder unit 22. The coating web is then fed to an induction heating unit 23 through which it passes to the nip between a pair of rolls 24. The laminate from the rolls 18 is also passed through the induction heating unit 23 to the rolls 24 where it is soldered to the web 19 in the presence of an inert gas atmosphere.

CLAIMS

1. A self-supporting superconductor comprising a tape having a carrier layer supporting a cryostable superconducting material.

2. A tape according to claim 1, wherein the thickness of the tape is less than 4.5mm.

3. A tape according to claim 1 or claim 2, wherein the cryostable superconducting material comprises a laminate of a tape of superconductor and a tape of a material which conducts normally.

4. A tape according to claim 3, wherein the normally conducting material is copper or aluminium.

5. A tape according to any of the preceding claims, wherein the superconducting material is niobium titanium.

6. A tape according to any of the preceding claims, wherein the carrier layer is ferro-magnetic.

7. A tape according to claim 6, wherein the carrier layer is steel.

8. A tape according to any of the preceding claims formed into a coil.

9. A tape according to claim 8, wherein the coil has a radius in the range 3-10m, preferably 5m.

10. A self-supporting superconductor substantially as hereinbefore described with reference to the accompanying drawings.

11. A method of manufacturing a self-supporting superconductor according to any of the preceding claims, the method comprising bonding separate tapes defining the carrier layer and the cryostable superconducting material.

12. A method according to claim 11, wherein the superconducting material is in the form of separate superconducting tape and normal conductor, the method further comprising bonding the two subsidiary tapes together.

13. A method according to claim 11 or claim 12, wherein the bonding process comprises roll bonding.

14. A method according to any of claims 11 to 13, wherein the bonding process comprises ultrasonic soldering and/or induction heating.

15. A method of manufacturing a self-supporting superconductor substantially as hereinbefore described with reference to the accompanying drawings.

16. An energy storage device comprising a number of coils according to any of claims 1 to 10 or manufactured in accordance with any of claims 11 to 15.

17. A device according to claim 16, wherein the coils are arranged in the form of a torus.

18. A device according to claim 17, wherein the cross-section of the torus is defined by an array of coils.

19. A device according to claim 17 or claim 18, wherein the radius of the torus is in the range 7-15m, preferably substantially 11.5m.

20. An energy storage device substantially as hereinbefore described with reference to the accompanying drawings.

The Patent Office

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Application No: GB 9525833.1
Claims searched: 1 to 20

Examiner: J L Freeman
Date of search: 5 February 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1A (AE); H1P (PSC, PSM)

Int Cl (Ed.6): H01B (12/00, 12/02, 12/06); H01F (6/00, 6/06); H01J (15/00)

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	GB 2257437 A	(General Electric Company) Page 2 line 21 to page 3 line 25.	1, 3, 4, 6-8, 11-13 & 16
X	GB 1391357	Thomson-Brandt) Page 3 line 74 to page 3 line 5.	1, 3, 4, 6, 7 & 8.
X	GB 1387941	(Union Carbide) Page 3 line 48 to page 5 line 25.	1, 3, 4, 8 & 16.
X	GB 1228646	(General Electric Company) Whole document.	1, 3, 4, 6-8, 11-13.
X	GB 1160566	(General Electric Company) Whole document.	1, 3-8 & 11-14.
X	WO 94/12991 A	(General Electric Company) Pages 5 & 7.	1, 3, 4, 6-8, 11-13 & 16

X Document indicating lack of novelty or inventive step
Y Document indicating lack of inventive step if combined with one or more other documents of same category.
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A Document indicating technological background and/or state of the art.
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E Patent document published on or after, but with priority date earlier than, the filing date of this application.